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**Relationships between leaf and root area indices and soil suction induced
during drying-wetting cycles**

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Abstract

The stability and serviceability of geotechnical infrastructure may be affected by plant-induced soil suction during drying-wetting cycles, because an increase in suction would reduce hydraulic conductivity and also increase shear strength. Recent studies have been conducted to quantify suction induced during evapotranspiration (ET) and ponding in soil vegetated with non-crop species that are used for the ecological restoration of geotechnical infrastructure. However, induced suction distribution under drying-wetting cycles has not been investigated. The objectives of this study are to (1) quantify suction induced by a non-crop tree species, *Schefflera heptaphylla*, under ponding-drying-ponding cycles and (2) correlate intercepted radiant energy, tree leaf area index (LAI), extinction coefficient (k) and root area index (RAI) with suction. In total, 18 vegetated soil samples with LAI ranging from 0.9 to 3.1 and three bare soil samples (control) were tested and subjected to identical cycles of ET and ponding. Energy balance calculation was performed to determine the percentage of interception of radiant energy. An almost linear relationship can be seen between the percentage of energy intercepted (from 7% to $42\% \pm 4\%$) and LAI (from 0.9 to 3.1 ± 0.09) for *S. heptaphylla*. The measured value of k for *S. heptaphylla* (0.13) was found to be much lower than that of some crop species (0.4-1.6) reported in the literature. Peak suction is always identified at the depth, where RAI is maximum. It was further demonstrated that the tree-induced suction has a strong linear correlation with both the RAI and LAI.

Keywords: Soil suction, *Schefflera heptaphylla*, evapotranspiration, drying-wetting cycles, leaf area index, root area index

Introduction

Schefflera heptaphylla (*S. heptaphylla*) is a tree species that is commonly used for the ecological restoration and rehabilitation of geotechnical infrastructure such as man-made slopes/embankments (Hau and Corlett, 2003; Garg et al., 2015a; Garg et al., 2015b; Garg and Ng, 2015; Leung et al., 2015a, b, c). This species is often selected because of its high survival rate (Hau and Corlett, 2003) and drought tolerance when vegetated in densely compacted soil of up to 95% relative compaction (TDOT, 1981; GCO, 2000). The water demand and water availability of this type of species are different from those of crop species, which are typically grown in relatively loosely compacted soil containing a relatively high nutrient content and subjected to regulated irrigation (Qadir and Oster, 2004). In addition, evapotranspiration (ET) by non-crop species such as *S. heptaphylla* could affect the hydrology and, hence, stability of geotechnical infrastructure. This is because ET induces soil suction and this in turn reduces hydraulic conductivity (Ng and Leung, 2012), which could have direct influence on the magnitude and distribution of suction and, hence, shear strength mobilised, during rainfall. Study of ET and soil suction/moisture also plays a significant role to improve the productivity of ecological infrastructure such as wetlands (Mitsch and Reeder, 1992; Raich and Schlesinger, 1992; Zhang et al., 2002; Zhang and Mitsch, 2005).

Various studies have been reported to quantify soil moisture/suction under drying (i.e., ET) and wetting (i.e., rainfall or ponding) events in soil vegetated with non-crop species (Simon and Collison, 2002; Smethurst et al., 2006; Fan and Su, 2009; Pollen-Bankhead and Simon, 2010; Smethurst et al., 2012; Ghestem et al., 2014; Veylon, 2015; Leung et al., 2015a, b). In most of these studies, a mix of species was used, making it very hard (if not impossible) to identify the root characteristics of those species and, more importantly, to understand their correlation with suction. Previous studies have shown that soil suction induced by soil vegetated with a crop species have some correlations with the leaf and root

characteristics (López et al., 2001), including leaf area index (LAI; a dimensionless index defining the ratio of total one-sided green leaf area to projected crown area perpendicular to the soil surface of an individual isolated plant) and root area index (RAI; a dimensionless index normalising total root surface area for a given root depth by the plan cross-sectional area of soil). However, any of such correlation for non-crop species like the *S. heptaphylla* is not well understood. It is also not known whether such correlation derived under a drying event can be applicable to that under a wetting event, which is of major concern for engineers to design slope stability. Previous studies have also shown that extinction coefficient (k ; a projected area of a leaf, relative to the projected area of a horizontal leaf of the same size) has a direct influence on energy interception and hence transpiration (Campbell and Norman, 1989). The higher the k value, the more horizontally inclined the leaf (i.e., cosine of leaf angle) would be. Study of such effect on transpiration-induced suction is rare, especially for non-crop species.

The objectives of this study are therefore (i) to quantify suction induced by *S. heptaphylla* and compare that with suction in bare soil during ponding-drying-ponding cycles; and hence (ii) to explore new correlations to link induced suctions with the amount of energy interception, as well as some plant parameters including k LAI and RAI of *S. heptaphylla*.

Materials and methods

Test plan

A test plan is designed to quantify and compare suction responses between bare (control) and vegetated soil in laboratory. In total, 18 tree seedlings with six different LAIs (i.e., 0.9, 1.5, 2.3, 2.6, 2.9 and 3.1) were tested to take into account any effects of natural variability. For each LAI, three replicates, whose LAIs were within $\pm 3\%$ of each other, were tested. The three seedlings with an average LAI of 2.9 were transplanted to test boxes labelled as R1-a,

R1-b, R1-c. Similarly, the boxes for the seedlings with average LAIs of 2.3, 0.9, 1.5, 2.6, and 3.1 are labelled as R2 (a, b and c), R3 (a, b and c), R4 (a, b and c), R5 (a, b and c) and R6 (a, b and c), respectively. Three bare soil samples were also used for measurements.

Experimental setup and instrumentation

Twenty one test boxes (300 mm x 300 mm x 350 mm; width x length x depth) were designed and built in this study. The size of the boxes was more than 2.5 times the root depth and root lateral diameter to minimize any boundary effects. Figure 1 shows a schematic diagram of a test box. Soil was compacted in each box, while a tree seedling was transplanted to the centre of each box. Nine drainage holes each with a diameter of 5 mm were drilled in the base of each test box for bottom drainage during testing. All boxes were tested in an atmosphere-controlled plant room, where the air temperature, radiant energy and relative humidity were maintained at 22.3 ± 1 °C, 1.9 ± 1 MJm⁻² and 53 ± 7 %, respectively. Based on Penman (1948)'s equation, the selected mean values of relative humidity and radiant energy correspond to a potential evapotranspiration (PET) rate of 1 mm/day. This evapotranspiration rate is similar to the observed average rate during the winter rainy season in Hong Kong (based on data from 1954-2009; Hong Kong Observatory). Side boundaries were kept impermeable. Heat dissipation matric water potential sensors (HDSs), which can reliably measure relatively high suction range (up to 350 kPa), were installed at shallow depths (30 mm and 80 mm) because suction developed by ET during a drying period could exceed 90 kPa (the measurement limit of a tensiometer) in the presence of roots in the top 80 mm of soil. Outside the root zone (i.e., 140 mm and 210 mm), tensiometers were installed to measure suction less than 90 kPa.

To provide radiant energy to the tree seedlings, a cool white fluorescent lamp capable of emitting light with wavelengths ranging between 400 and 700 nm was mounted on the top of each vegetated box (see Fig. 1). This particular waveband lies within the range of solar

radiation (known as photosynthetically active radiation) required by chloroplasts in the process of photosynthesis. Radiant energy was measured at the soil surface inside and outside the canopy coverage of a seedling so as to quantify the amount of energy received at the soil surface as well as the energy intercepted by tree leaves.

Soil type and box preparation

Completely decomposed granite (CDG), which is common in Hong Kong, was selected for testing. Results from sieve and hydrometer analyses show that the gravel, sand, silt and clay contents of CDG were $19 \pm 3\%$, $42 \pm 5\%$, $27 \pm 7\%$, and $12 \pm 4\%$, respectively. Based on the particle-size distribution and Atterberg limit ($26 \pm 4\%$ of plastic limit and $44 \pm 5\%$ of liquid limit), CDG is classified as clayey sand with gravel (SC), according to the Unified Soil Classification System (USCS). Measured drying and wetting soil water retention curves for this type of soil were reported in Leung et al. (2015). They found that the air-entry value of the compacted CDG was about 1 kPa. For any given suction, volumetric water content along the drying path is always higher than that along the wetting path, showing a marked hysteresis loop. Saturated hydraulic conductivity of the compacted CDG was found to be 1.7×10^{-7} m/s (Leung et al., 2015b). In each test box, a 280 mm thick layer of SC was compacted to a dry density of $1500 \text{ kg m}^{-3} \pm 2\%$ (i.e., equivalent to 80% of the maximum dry density) at water content of 12% (by mass) using the undercompaction method (Ladd, 1977).

Test procedures

All tests were conducted in the plant room in three stages. The first stage was to establish comparable initial suction distributions and hence hydraulic conductivities among all boxes (Ng and Leung, 2012). In this stage, the soil surface of each box was ponded until (i) there were zero suction at all four instrumented depths and (ii) percolation through the drainage

holes in the base of the box was observed. Then, the soil surfaces of all boxes were covered to prevent any loss through evaporation/evapo-transpiration, while the nine holes in the base of each box remained open for free drainage. Variations in suction were monitored continuously until their profiles became comparable and any drainage from holes stopped.

The second stage was to expose the soil surface of all boxes to continuous lighting at a radiant energy of 1.9 MJ/m² in the plant room for two days (days 0 to 2). Any suction induced at depths of 30 and 80 mm was recorded by the HDSs, while that induced at depths of 140 and 210 mm were registered by tensiometers. In the third stage, the soil surface of each test box was ponded with 6 mm/min of water head for one minute. The applied ponding was equivalent to a rainstorm having a return period of about 100 years in Hong Kong (Lam and Leung, 1995). At all stages of testing, all bottom drainage holes of each box were remained open for free drainage.

After the three-stage testing, each tree seedling was carefully removed from the test box and the root depth and RAI were determined using Image J as per procedures described in Garg et al. (2015a) in details. The mean peak RAIs for tree seedlings vegetated in the R1, R2, R3, R4, R5, and R6 groups of boxes were found to be 1.05, 0.75, 0.5, 0.64, 0.9 and 1.1, respectively. The range of depth where the mean peak RAI were identified were 70 to 80 mm, as similar found in previous studies (Leung et al., 2015a, b; Garg et al., 2015a, b) when the same species was vegetated in the same soil type. Table 1 summarizes the measured mean RAI and LAI of each group of boxes.

Figure 2 correlates RAI with LAI from the 18 seedlings of *S. heptaphylla* tested in this study. It can be seen that an almost linear correlation ($R^2 = 0.96$) exists between these two plant parameters. As all the data points are well below the 1:1 line, this suggests that a relatively large increase in LAI from 0.9 to 3.1 only results in a small increase in RAI. On the contrary, for the Sitka spruce (*Picea Sitchensis*) forest investigated by Butler et al. (2010),

they found that an increase in LAI by 1.7 times (4.8 to 8.5) is associated with a four times increase in RAI (i.e., 0.28 to 1.0). The observed difference might be because water was more easily accessible in the laboratory conditions due to the artificial applied irrigation than that in the field condition, where no scheduled irrigation was supplied. Following the work by Sperry et al. (1998) and Reich (2002), a higher RAI/LAI ratio can signify the ability of a plant species to withstand dry soil conditions. Alternatively, one may also interpret that a lower RAI/LAI ratio indicates there is ample supply of ground water for plants to grow.

Results and discussion

Influence of trees on measured suction profile

Figure 3(a) compares the measured distributions of suction along depth between the group of boxes containing bare soil (the B group) and the R1 group of boxes containing vegetated soil during the first two days of ET (i.e., the 2nd stage of test). It can be seen that before testing the initial suction profiles were similar for all three groups of boxes. After two days of ET, suction at all depths in both bare and vegetated boxes increased. Due to the relatively high hydraulic gradient near the soil surface upon evaporation, the measured suction at shallower depths in bare boxes (the B group) was higher than that at deeper depths. On the contrary, suction below 140 mm depth distributed uniformly along depth, suggesting that the hydraulic gradient was almost equal to one. The approximate unit gradient flow meant that water flow was driven by gravitational head gradient mainly towards the bottom drainage holes.

For the vegetated boxes, suction at all depths also increased, but is found to peak at much greater depth of 80 mm, where peak RAI was identified, instead of near the soil surface in the case of bare soil. At a depth of 30 mm, the vegetated boxes recorded slightly lower suction than the bare boxes. This is likely because compared to the bare boxes where the soil surface received the full amount of radiant energy for evaporation, less amount of the energy

was received by the vegetated boxes due to energy interception by tree leaves. At deeper depths (140 and 210 mm) below the root zone, the suction induced in the vegetated boxes was similar to that by the bare boxes. This suggests that the influence zone of suction induced by the two days of ET was within the root zone mainly.

Figure 3(b) compares the responses of suction profiles before and after ponding (i.e., 3rd stage of test) between the bare boxes and the R1 group of vegetated boxes. After ponding, suction in the bare boxes exhibited a fairly uniform profile with an average value of 40 ± 2 kPa, indicating that there was a unit gradient downward flow. Although similar suction was recorded at depths of 30, 140 and 210 mm between the bare and vegetated boxes, 200% to 300% more suction was retained in the vegetated boxes than in the bare boxes at the depth, where the maximum RAI was identified (i.e., 80 mm). Since the applied rate of ponding (i.e., 6 mm/min) was much higher than the PET in the plant room (i.e., 1 mm/day or 0.001 mm/min), any suction induced by transpiration during ponding might not be the major reason behind the observed higher suction retained in the vegetated soil. It may be also seen that the higher the initial suction before ponding, the higher the amount of suction retained after ponding would be, probably because of the reduction in hydraulic conductivity due to the additional suction induced by tree ET during the previous drying stage. On the contrary, some studies (Angers and Caron 1998; Carminati and Vetterlein, 2012; Veylon et al. 2015) on plant species vegetated in relatively loose soil (i.e., 800 – 1000 kg/m³) suggest that the presence of roots might create micro-cracks and aggregates, which would then result in a change in soil structure and hence hinder the development of suction.

Correlation between intercepted energy, tree characteristics and soil suction

Based on the setup shown in Fig. 1, an energy balance equation may be expressed as follows:

$$R_i = (R_s + R_{rs}) + (R_l + R_{rl}) + H \quad (1)$$

where R_i is incoming radiant energy from the lamp (i.e., 1.9 MJ/m² in this experiment); R_s is energy received at the bare soil surface; R_{rs} is energy reflected from the bare soil surface; R_l is energy intercepted by the tree leave surface; R_{rl} is energy reflected from the tree leave surface; and H is air heat flux (commonly known as sensible heat flux). Both R_{rs} and R_{rl} can be neglected due to low albedo (i.e., the ratio of reflected energy to incoming energy) of a bare soil surface (0.13 – 0.17; Murphy and Lodge, 2001) and a tree leaf (0.10 – 0.15; Taha et al. 1988). The energy used to heat up air (i.e., H) can also be neglected due to the low relatively specific heat capacity of air (i.e., $H \approx 0$). As a result, Eq. (1) may be simplified as follows:

$$R_i = R_s + R_l \quad (2)$$

This equation physically means that a certain portion of the incoming radiant energy R_i is received at bare soil surface (i.e., R_s) for evaporation, whereas the remaining portion is intercepted by tree leaf surfaces (i.e., R_l) for transpiration. A portion of R_l is also absorbed by chlorophyll for the process of photosynthesis. However, that amount is usually less than 2%; (Salisbury and Ross, 1992) and is therefore not considered in the energy balance equation.

Figure 4(a) shows the variation in maximum mean energy intercepted (expressed as a percentage; i.e., R_l/R_i) with the LAI of tree seedlings. In general the mean energy intercepted increased from 7% to 42% \pm 4% as LAI increased from 0.9 to 3.1. The observed positive correlation is somewhat expected because the higher the LAI, the greater the leaf surface area for intercepting the incoming radiant energy. The observed correlation seems to be closer to trend predicted by the Beer-Lambert law (Ritchie, 1972), when the k in the law is set to 0.13. The value of k determined for *S.heptaphylla* is much lower than that observed for various crop species (0.4 to 1.6) (Impens and Leumer, 1969; Zhang et al., 2014), but it is close to some tree species found in Mediterranean forest ($k = 0.212$) and coniferous forest ($k = 0.363$) as studied by Brivio et al. (2006). The observed lower k value in this study suggests that the leaves of the non-crop species, *S. heptaphylla*, inclined more vertically than that of crop

species. This is consistent with the laboratory observation that most of the leaves of *S. heptaphylla* tended to incline predominantly sub-vertically.

Correlations between tree-induced suction and LAI for all five groups of the vegetated boxes (i.e., 18 tree individuals altogether) are shown in Fig. 4(b). In order to highlight the effects of tree transpiration, suction in the y-axis of the figure is expressed as the mean suction difference between vegetated and bare soil, Δs , at a depth of 80 mm, where RAI is maximum. Positive Δs indicate an additional unit of suction induced in a particular group of vegetated boxes. A linear regression analysis shows that the Δs recorded after two days of ET has a strong correlation with LAI ($R^2 = 0.91$). This is consistent with the correlation shown in Fig. 4(a), which shows that a tree having a higher LAI intercepted a greater amount of radiant energy interception. A higher LAI value means that there are more stomata on tree leaves to receive more energy for transpiration (Kelliher et al. 1995). Note that any correlation between LAI and Δs after the ponding event is not shown because the tree transpiration rate was minimal, as compared to the applied rate of ponding. The amount of energy intercepted is thus not expected to contribute significantly to the suction retained.

Figure 5 shows the relationship between Δs and mean peak RAI at 80 mm depth. Each mean peak RAI is taken to be the average of peak RAIs observed for each group of boxes. It can be seen that all six groups of vegetated boxes showed positive Δs , which means that the tree seedlings were capable of retaining additional suction beyond that retained in bare soil at this particular depth after the wetting event. As expected, for any given RAI, the magnitude of Δs measured after ponding was always lower than that after the drying event because of water infiltration. RAI is found to have strong correlations (R^2 up to 0.97) with both the Δs recorded after two days of ET and that after ponding). It is obvious that the ability of root-water uptake of the tree to induce suction is strongly linked to the root surface area. However, as compared to non-crop species, the correlation trend between RAI and soil suction (or

moisture) is negative for crop species (Ross and Hegarty, 1979; Pandey et al., 1984; Merrill et al., 2002). These existing studies generally show that soil suction decreases with an increase in root area ratio (or root biomass, root length density). This may be because of differences in root water uptake ability (i.e., transpiration reduction function) for crop species than that for non-crop species (Garg et al., 2015c). Also, the correlations may depend on the growth rate of vegetation (Hupet and Vanclooster, 2002). It can be also observed from Fig. 5 that the values of Δs of R3 (for both cases, before and after ponding) are close to 0. This seems to suggest that there exists a threshold RAI, below which the effects of *S. heptaphylla* on the induced soil suction become negligible. Table 1 summarizes the mean values of the percentage of energy interception and the measured mean Δs before and after ponding of the 18 seedlings of *S.heptaphylla*. Based on the correlations revealed in Figs 4 (b) and 5, it is fairly clear that suction induced by *S. heptaphylla* is governed by the two plant parameters, LAI and RAI, which are themselves positively correlated (Fig. 2). In addition, for this particular species, there exists a threshold RAI (i.e., ~ 0.5) and a threshold LAI (~ 1.0), below which hydrological contribution from the species is insignificant.

Conclusions

This study quantified and compared suction induced under ponding-drying-ponding cycle in clayey sand with gravel with and without *S. heptaphylla*. Based on the results obtained from the 18 tree seedlings, measured suction distributions in vegetated soil were correlated and interpreted with measured interception of radiant energy by tree leaves, as well as some tree characteristics including LAI and RAI. An extinction coefficient, which is an important parameter for indicating leaf angle (hence percentage of intercepted energy) was also determined for *S.heptaphylla*.

After subjecting the seedlings to two days of ET, the influence zone of suction induced by vegetation was limited to the root zone. A comparison of the measured suction profiles between vegetated and bare soil samples showed that the suction induced in vegetated soil peaked at the maximum RAI (i.e., 80 mm below the surface), whereas that induced in bare soil peaked near the soil surface. Depending on the amount of energy intercepted by leaves, the peak suction measured in vegetated soil at a depth of 80 mm can be 100% – 200% higher than in bare soil because of additional suction induced by transpiration. An almost linear relationship can be identified between the percentage of energy intercepted (from 7% to 42% \pm 4%) and LAI (from 0.9 to 3.1 \pm 0.09). The extinction coefficient of *S. heptaphylla* (0.13) using Beer-Lambert's law was found to be much lower than that for crop species (0.4-1.6), suggesting that the leaves of *S. heptaphylla* inclined more vertically than in some crop species reported in the literature.

Upon ponding with a return period of 100 years, the influence zone of suction was also identified to be within the root zone. At the depth where the maximum RAI was identified, between 100% and 300% more suction was retained in the vegetated soil than in the bare soil. It is revealed that the induced suction are strongly and positively correlated ($R^2 = 0.91 - 0.97$) with both RAI and LAI. Based on the identified correlations, there exists a threshold RAI (i.e., ~ 0.5) and a threshold LAI (~ 1.0), below which hydrological contribution from the species is insignificant.

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Table 1. A summary of measured mean values of LAI, RAI, percentage of energy interception and Δs before and after ponding

Test box	LAI [-]	RAI [-]	Energy interception [%]	Δs [kPa] (before ponding)	Δs [kPa] (After ponding)
R1	2.9	1.05	30	97	48
R2	2.3	0.75	25	50	28
R3	0.9	0.5	7	4	2
R4	1.5	0.64	15	31	18
R5	2.6	0.9	27	36	9
R6	3.1	1.1	42	101	52

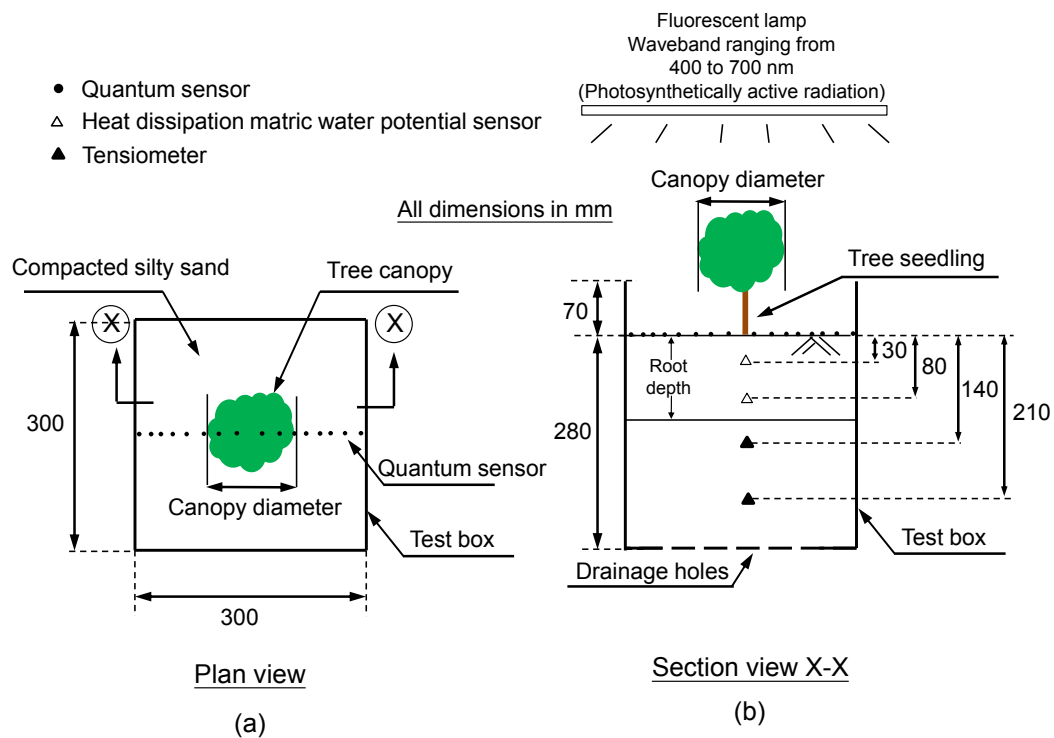


Fig. 1. Schematic diagram showing a typical setup of a vegetated test box and instrumentation (a) plan view and (b) cross-sectional view X-X

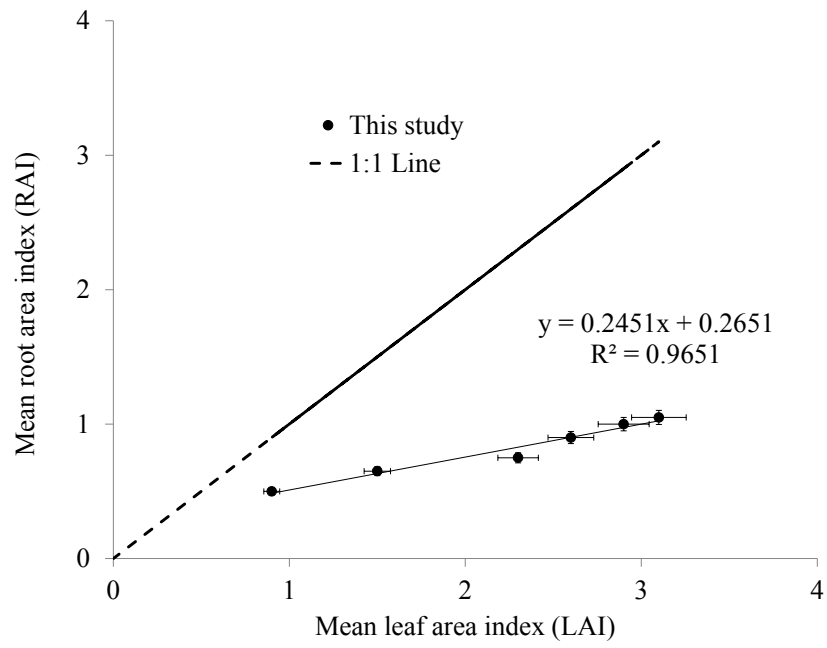


Fig. 2 Correlation between mean peak RAI (at 80 mm depth) and LAI of *S. heptaphylla*

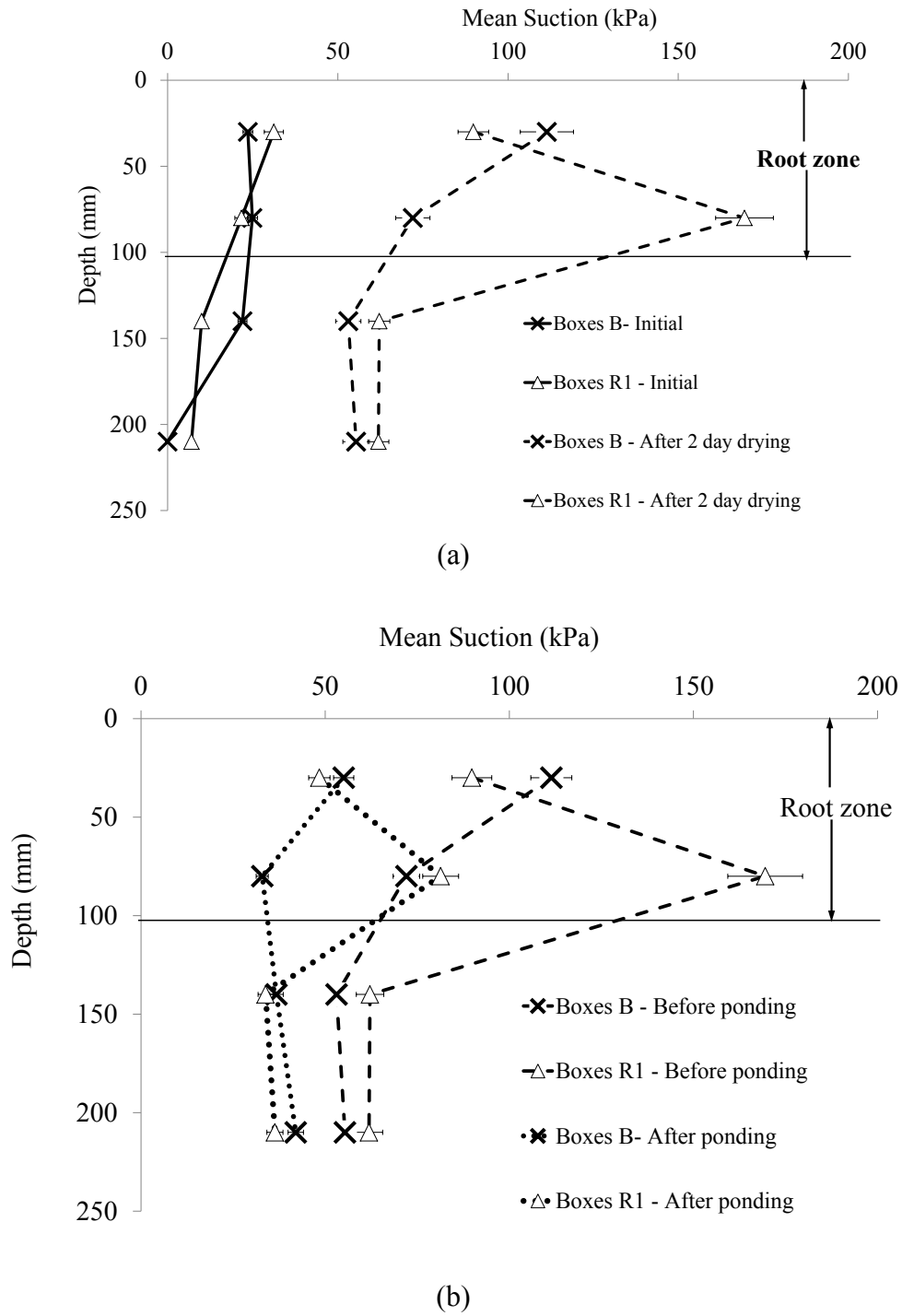
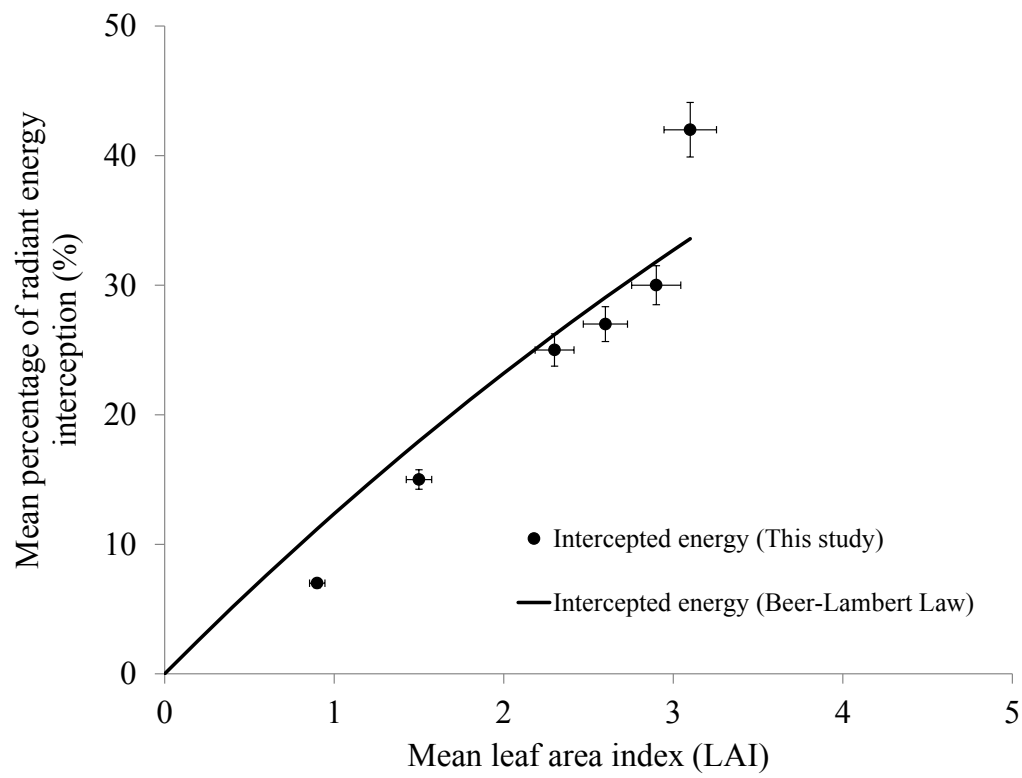
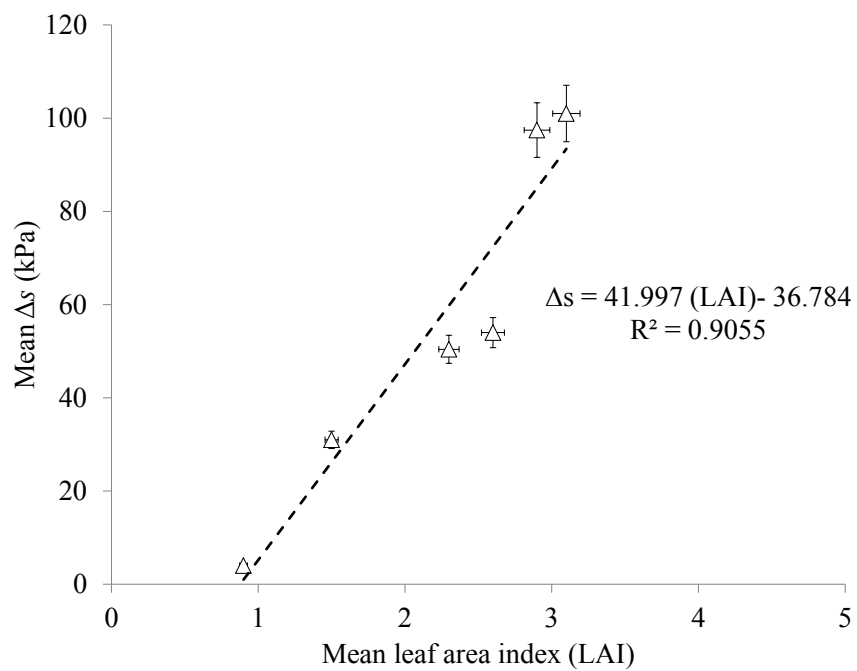


Fig. 3. Comparison of measured mean suction profiles between bare and vegetated boxes during (a) two days of ET and (b) the subsequent ponding event. Error bars represent standard deviations.



(a)



(b)

Fig 4. Relationships between mean LAI and (a) the mean percentage of radiant energy intercepted and (b) mean Δs (during drying stage) at a depth of 80 mm

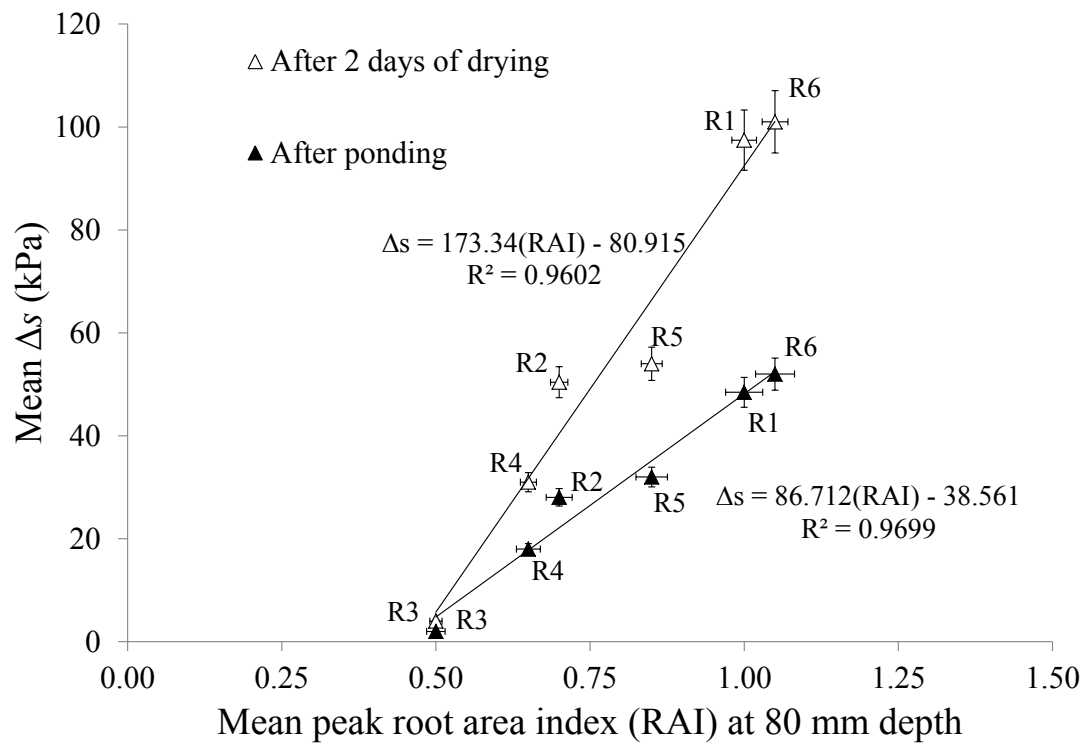


Fig. 5. Relationships of mean Δs and mean peak RAI before and after ponding